Simulation of Benthic Ripples and Transport Processes for SAX

Oliver B. Fringer
Terman Bldg., Room M17
Dept. of Civil and Environmental Engineering
Stanford University, Stanford, CA 94305-4020
phone: (650) 725-6878 fax: (650) 725-9720 email: fringer@stanford.edu

Robert L. Street
Environmental Fluid Mechanics Laboratory, Room 524 R
Dept. of Civil and Environmental Engineering
Stanford University, Stanford, CA 94305-4020
phone: (650) 723-4969 fax: (650) 725-9720 email: street@stanford.edu

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LONG-TERM GOALS

Our goal is to provide a complete simulation code that will represent and predict the sediment transport and bed features on the continental shelf at user-specified resolution by using state-of-the-art algorithms for the physics and numerics of the simulation code.

OBJECTIVES

Our primary objective is to simulate the ripple climate on the bed of the inner shelf at depths on the order of 20 m and over domains ranging from centimeters to kilometers in support of the Ripples DRI experiments and analyses. Our secondary objective is to use simulation to better understand the physics of ripple formation and sediment transport in this environment. A third objective is to create a powerful and fast parallel numerical code system by the synthesis of a number of our computational tools.

APPROACH

We are developing a multiscale simulation code that will represent and predict the sediment transport and bed features on the continental shelf via an integrated modeling framework that couples a laboratory-scale large-eddy simulation code with our field-scale nonhydrostatic coastal ocean model SUNTANS (Fringer et al., 2006). Ultimately, the wave climate as predicted by SUNTANS will drive the formation of ripples in the small-scale code, which would in turn alter the bottom roughness as seen by the waves, and alter their behavior accordingly. Using this tool we will have the ability to predict the evolution of waves and benthic ripples on coastal shelves and in shallow embayments given the distribution of sediment properties and the incoming wave field. The components of the multiscale simulation code are described below.

For the field-scale solver, we are using the parallel unstructured grid code, known as SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator), which

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solves the nonhydrostatic Navier-Stokes equations under the Boussinesq approximation with the large-eddy formulation for the resolved motions. The code has been developed by Fringer *et al.* (2006) in order to determine the behavior of the nonhydrostatic internal wave spectrum in Monterey Bay (Jachec et al., 2006). SUNTANS is a high-resolution simulation tool for coastal, estuarine, and river simulations, and incorporates a host of processes, from the free-surface to the bed, that play an important role in driving smaller-scale motions, including the nonhydrostatic pressure, wind stress, surface and internal tides, and parameterizations of small-scale internal as well as surface breaking physics. Most importantly, because it is unstructured, and adaptive in the long-term, we have the ability to employ higher resolution around the site of interest for the Ripples DRI field experiments where we embed the smaller-scale simulation codes that we describe below.

The SUNTANS code is being used to determine the field-scale motions that drive the smaller-scale flow, which is computed with a nonhydrostatic parallel large-eddy simulation Navier-Stokes solver. This solver employs the code of Cui and Street (2001; 2004) (henceforth referred to as PCUI) which is an adaptation of the large-eddy simulation solver of Zang *et al.* (1994) to simulate laboratory-scale rotating stratified flows using MPI, the message passing interface, on parallel computers. The formulation of Zang *et al.* employs a non-orthogonal curvilinear, boundary-following grid as well as a dynamic-mixed subfilter scale model (Zang *et al.*, 1993) to compute the subfilter scale terms that arise from volume filtering. The equations are discretized in time with a semi-implicit, second-order accurate method and in space with second-order differencing and advanced with a fractional step/projection method. The method has been applied to a host of simulations, including turbulent stratified flow over a wavy bed (Calhoun *et al.*, 1999), interfacial breaking waves (Fringer & Street, 2003), and the study of a round jet in crossflow (Yuan *et al.*, 1999) using a total of 20 overlapping grids.

For sediment transport, we are employing algorithms from the code of Zedler and Street (2001; 2002; 2006), who extended the formulation of Zang *et al.* (1994) and added a module which solves the advection diffusion equation (with settling term) for the sediment. Under this work Zedler and Street also created a bed-load module and a bed erosion/deposition module (Zedler, personal communication, 2005) to go with the module for suspended sediment transport. Zedler provided us with the equations in the useful terrain-following coordinates of her original code so that the resolution of shear stress direction, for example, is clear. Motion of the bed in SUNTANS will be computed using a boundary-fitted curvilinear grid that moves with the bed, following the formulation of Hodges and Street (1999).

WORK COMPLETED

We have implemented the suspended sediment transport model into the PCUI code, including a new bottom boundary condition for sediment transport in large-eddy simulation. We have also implemented a boundary-fitted, moving curvilinear grid that follows arbitrary geometries and enables simulation of ripple formation and evolution while guaranteeing conservation of suspended sediment mass.

RESULTS

Our work to date has focused on incorporating the suspended-sediment modules of Zedler and Street (2001, 2006) into the parallel large-eddy simulation code PCUI (Cui and Street, 2001) in order to perform high-resolution simulations of sediment-ripple dynamics on parallel computers. We have

employed several modifications to the implementation of Zedler and Street, most notably the implementation of the bottom boundary condition for sediment, which does not require knowledge of the near-bed turbulence parameterization. In the formulation of Zedler and Street, the bottom boundary condition for the suspended sediment is given by

$$\frac{\nu_T}{\Pr}\frac{\partial \overline{C}}{\partial z} = -P_k \tag{1}$$

where ν_T is the eddy-viscosity, $\Pr_T$ is the turbulent Prandtl number, $\overline{C}$ is the grid-filtered sediment concentration (in a large-eddy simulation framework), z represents the vertical direction, and P_k is the pick-up function. Although the same formula was employed by van Rijn (1986) with a parabolic eddy-viscosity model, the drawback to using this boundary condition is that it can be highly restrictive when the magnitude of the eddy-viscosity is small, since, given a value of the pick-up function P_k, the near-bed gradient of the suspended sediment concentration is given by

$$\frac{\partial \overline{C}}{\partial z} = -P_k \frac{\Pr}{\nu_T} \tag{2}$$

Use of this formula to specify the bottom boundary condition for the suspended sediment concentration is prohibitive in a large-eddy simulation because the near-bed eddy-viscosity is small, particularly when high-resolution is employed.

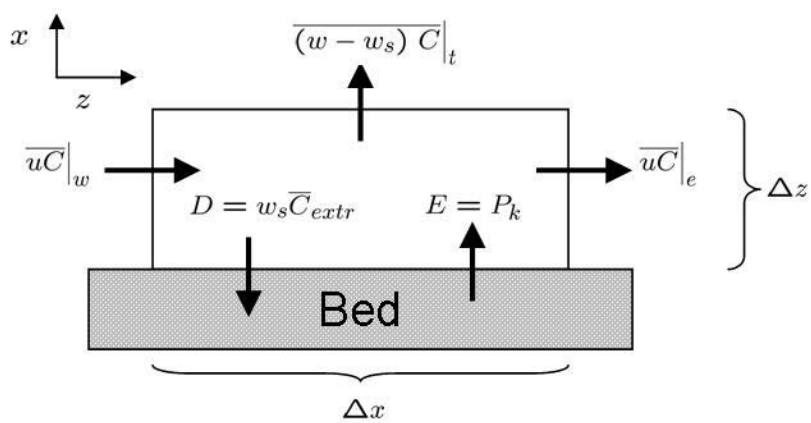

Figure 1: Two-dimensional schematic of a near-bed control volume of with Δx and height Δz, showing the filtered fluxes that influence the rate of change of the suspended sediment concentration within the control volume.

Our breakthrough was achieved by considering a finite volume form of the filtered transport equation for the suspended sediment. In what follows we derive it in two dimensions for illustrative purposes although we employ the three-dimensional case. The governing equation is obtained by filtering the transport equation for the suspended sediment and discretizing it over a two-dimensional finite volume of width Δx and height Δz, with the east-and west-face fluxes denoted by e and w, respectively, and the top and bottom-face fluxes denoted by t and b, respectively (see Figure 1), to obtain

$$\frac{\partial \overline{C}}{\partial t}+\frac{1}{\Delta x}\left[\overline{uC}\Big|_e-\overline{uC}\Big|_w\right]+\frac{1}{\Delta z}\left[\overline{(w-w_s)C}\Big|_t-\overline{(w-w_s)C}\Big|_b\right]=0\,, \tag{3}$$

where w_s is the settling velocity. The standard procedure in a large-eddy simulation is to employ a model for the unclosed terms $\overline{uC}$ and $\overline{wC}$, which arise from filtering the nonlinear transport terms. In our work we employ the dynamic-mixed model of Zang and Street (1993), which, for the vertical flux of sediment, gives

$$\overline{wC}=\overline{w}\,\overline{C}+\chi_3\,, \tag{4}$$

where the vertical subfilter-scale flux is given by the sum of a gradient-diffusion and the modified Leonard term $P_{i3}^m=\overline{\overline{w}\,\overline{C}}-\overline{\overline{w}}\,\overline{\overline{C}}$, such that

$$\chi_3=\overline{wC}-\overline{w}\,\overline{C}=-k_T\frac{\partial \overline{C}}{\partial z}+P_{i3}^m\,, \tag{5}$$

where $k_T=\nu_T/\mathrm{Pr}_T$ is the scalar diffusivity. Employing this model for the unclosed terms in equation (3) requires that all terms in equation (5) be specified at the bed (the b term in equation 3), thereby requiring a gradient-diffusion type model of the form given in equation (2). In order to avoid the aforementioned limitation associated with a small eddy-viscosity at the bed, we specify a boundary condition at the bed in equation (3) for the term at the bottom face ***before*** imposing a model to handle the unclosed terms. Specifically, in our formulation we impose a flux on the unclosed term at the bed of the form

$$\overline{(w-w_s)C}\Big|_b=E-D\,, \tag{6}$$

where the erosion is modeled with the pickup function $E=P_k$, and the deposition is given by $D=w_s\overline{C}_{extr}$, where $\overline{C}_{extr}$ is the value of the suspended sediment concentration at the bed that is obtained via extrapolation from interior points.

We have employed this boundary condition to simulate the dynamics of suspended sediment in a channel flow of length L=2.0 m, width W=1.0 m, and height H=0.6 m, and mean streamwise velocity of U=1 m s^{-1}, to yield a Reynolds number of 600 000 (based on Re=UH/ν, where $\nu=10^{-6}$ m^2 s^{-1} is the kinematic viscosity of water). The flow is started from rest and allowed to come to a statistically steady state, whereupon the sediment is initialized with a uniform distribution. As depicted in Figures 2(a)-(c), despite the existence of turbulent fluxes at the start of the simulation, and because there is no sediment supply at the top surface, gravitational settling dominates the behavior of the suspended sediment profiles. As a result, there is a strong downward sediment flux and the total concentration decreases rapidly during this initial settling period. Without turbulent diffusion, this process would persist until all sediment particles settle out. However, once turbulent transport becomes strong

enough, particularly when the near-bed concentrations become high due to sediment pickup, sediment is transported from the channel bed into the upper part of the water column. As depicted in Figures 2(c)-(d), turbulent diffusion becomes significant and this results in a net upward flux of sediment. During this transitional period, due to turbulent diffusion, the concentration field gradually increases with time due to erosion until the upward turbulent flux balances the downward flux due to settling. At this point, the suspended sediment concentration reaches a statistically steady state and profiles at each cross section remain statistically invariant (see Figures 2(e)-(f)).

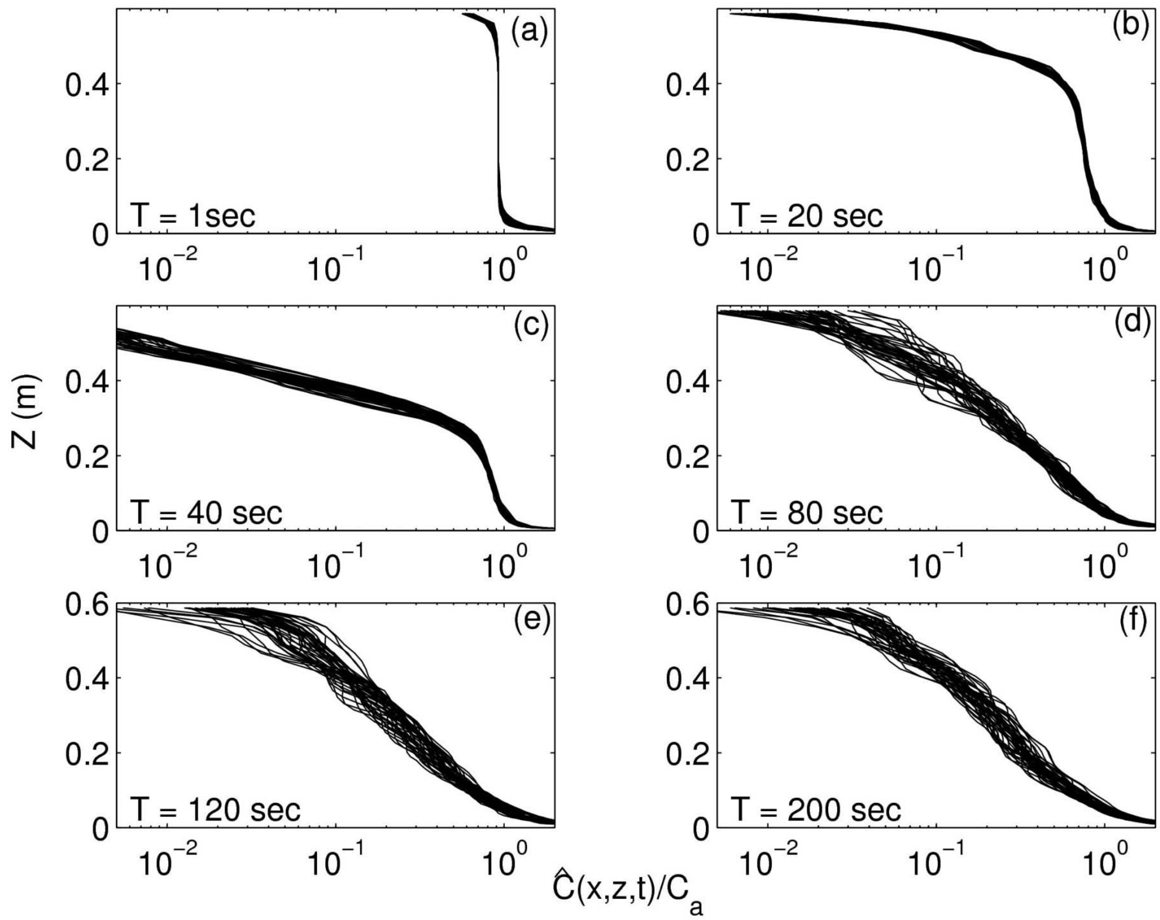

Figure 2: The temporal evolution of the laterally-averaged suspended sediment concentration profiles, normalized by the measured reference concentration C_a at 0.02 m above the bed. Each line represents a different streamwise location along the channel.

The strong spatial variability of the suspended sediment concentration is shown in Figure 3, which depicts the concentration contours in a vertical plane along the centerline at t = 1002 s. In order to further investigate how sediment suspension is linked to the ambient flow field, in Figure 4 we plot instantaneous concentration contours superimposed over the velocity vectors in a cross-sectional plane at x = 0.625 m. The figure shows transport of the suspended sediment associated with the resolved large eddies. Near the bottom, patches of high sediment concentration correspond to high eddy intensity or upward flux. These eddies form vortex cores and can extend downstream, thereby greatly enhancing sediment transport in the streamwise direction. Because the mean vertical sediment flux due

to the eddy-diffusion is much less than that induced by the resolved field, the transport of suspended sediment in our results is mainly due to advection by the resolved eddies. Once sediment is mobilized by the excess shear stress, which we model with the pick-up function, it is further suspended into the water column only if the ambient turbulent flux is strong enough to overcome the gravitational settling. Otherwise, suspended sediment will deposit at the bottom and its motion will be dominated by granular forces. This eddy-transport phenomenon is illustrated further by a zoom-in plot of Figure 4 in Figure 5, which depicts high sediment concentration with weak spatial variability near the bed and suspension of sediment due to the strong, coherent eddies and upward velocity. These near-bottom vortex structures and the associated sediment transport are also found by Zedler and Street (2001, 2006), who simulate high Reynolds number channel flow using LES with a different wall model and boundary conditions.

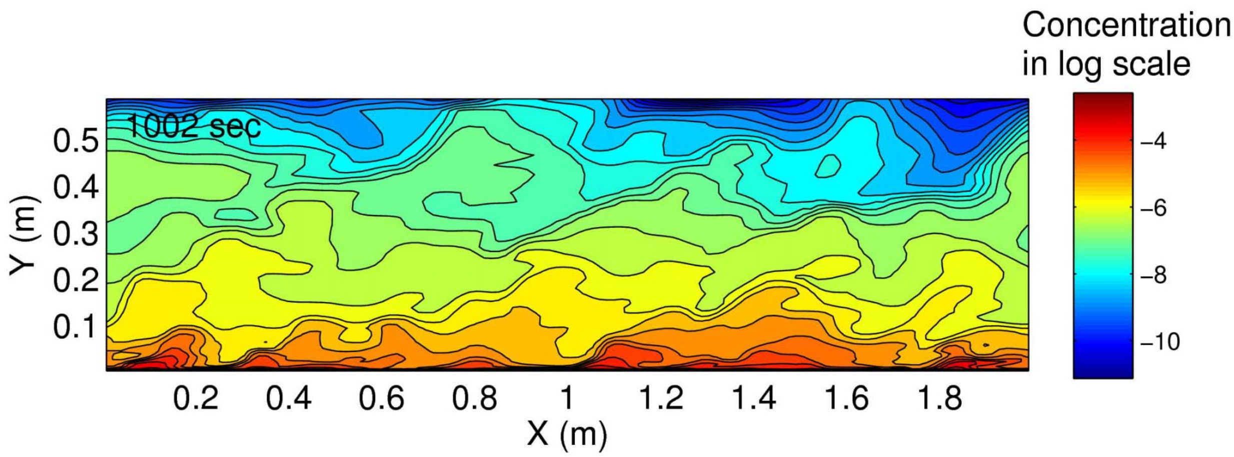

Figure 3: A snapshot of the concentration contours in a vertical plane along the channel centerline at t = 1002 s.

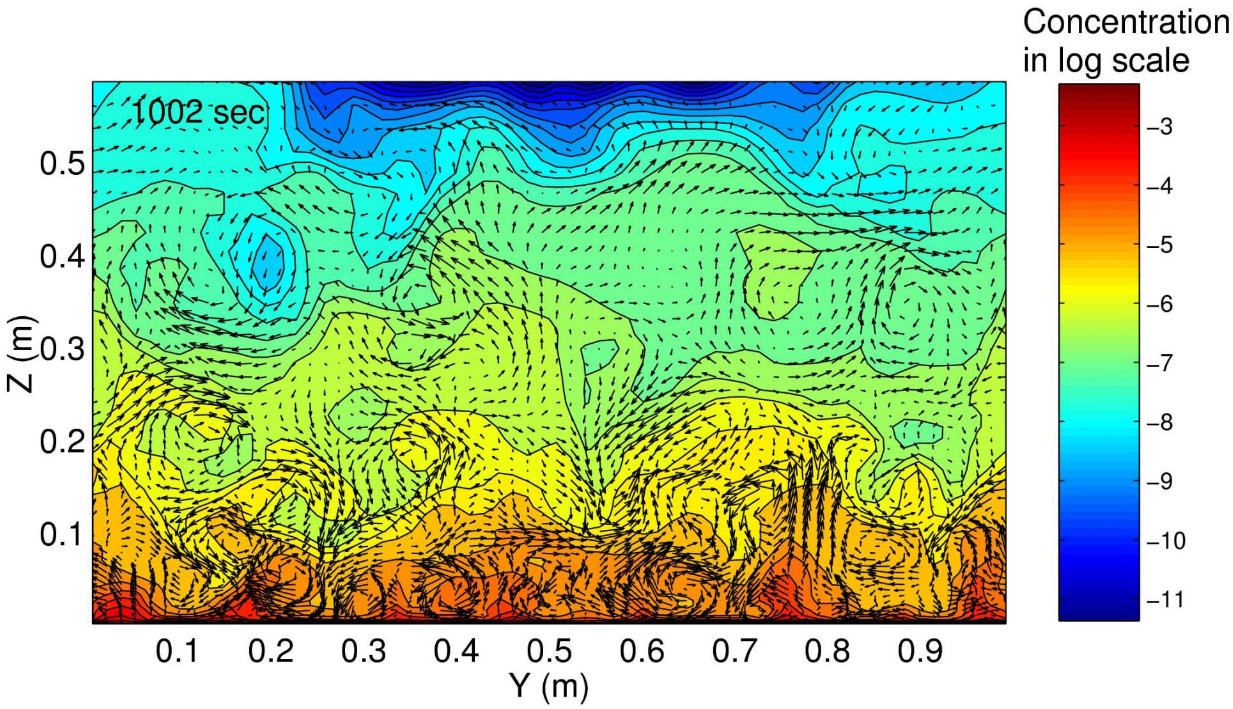

Figure 4: Velocity vectors superimposed over the concentration contours in a cross-sectional plane at x = 0.625 m and t = 1002 s.

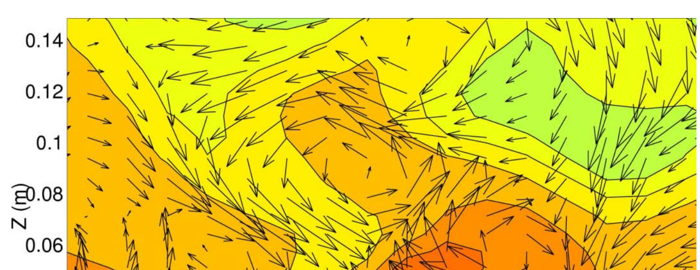

Figure 5: A zoom-in view of Figure 4 in the region where high concentration is associated with the strong near-bottom eddy and upward flow.

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